Compton Imaging Tomography: A New Approach for 3D NDI of Complex Components

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Our Motivation: To Address Difficult Problems That Cannot Be Handled with Conventional NDI Technologies

Typical Aerospace Industry NDI Requirements:

- NDI of large structures (need one-sided approach)
- NDI of non-uniform, multilayer, or composite structures
- Applicability to conductive and non-conductive materials
- 3D defect detection and visualization capability
- High resolution and contrast
- Non-contact operation

Target Applications

Space Industry:

- In-space assessment of damage to spacecraft and habitable structure components
- On-ground NDI/NDT for R&D and component qualification

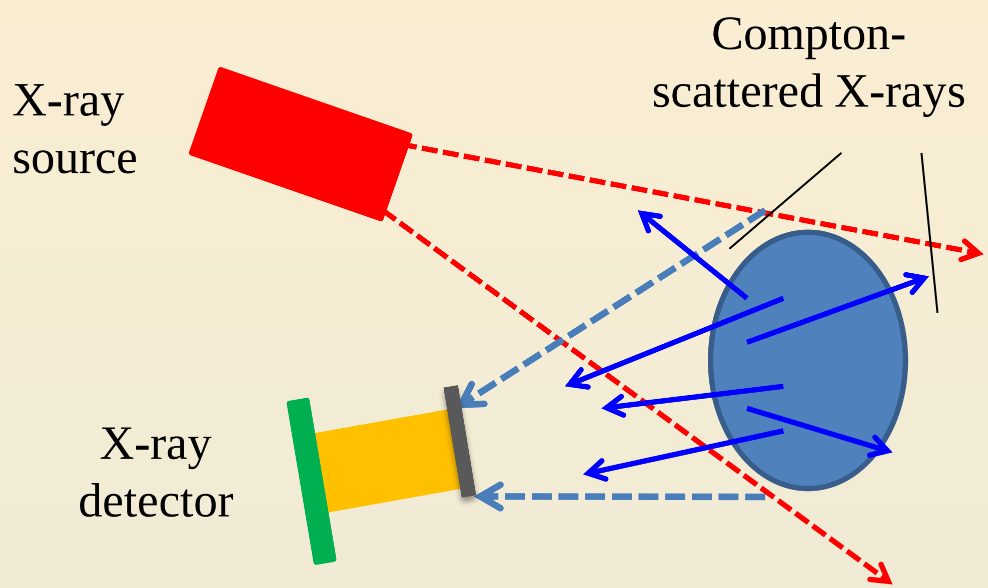
Aircraft NDI:

- Detection of corrosion and cracks in aluminum alloy and composite aircraft panels
- Detection of damage and disbonding in honeycomb structures

X-Ray Compton-Based Techniques Have Several Advantages:

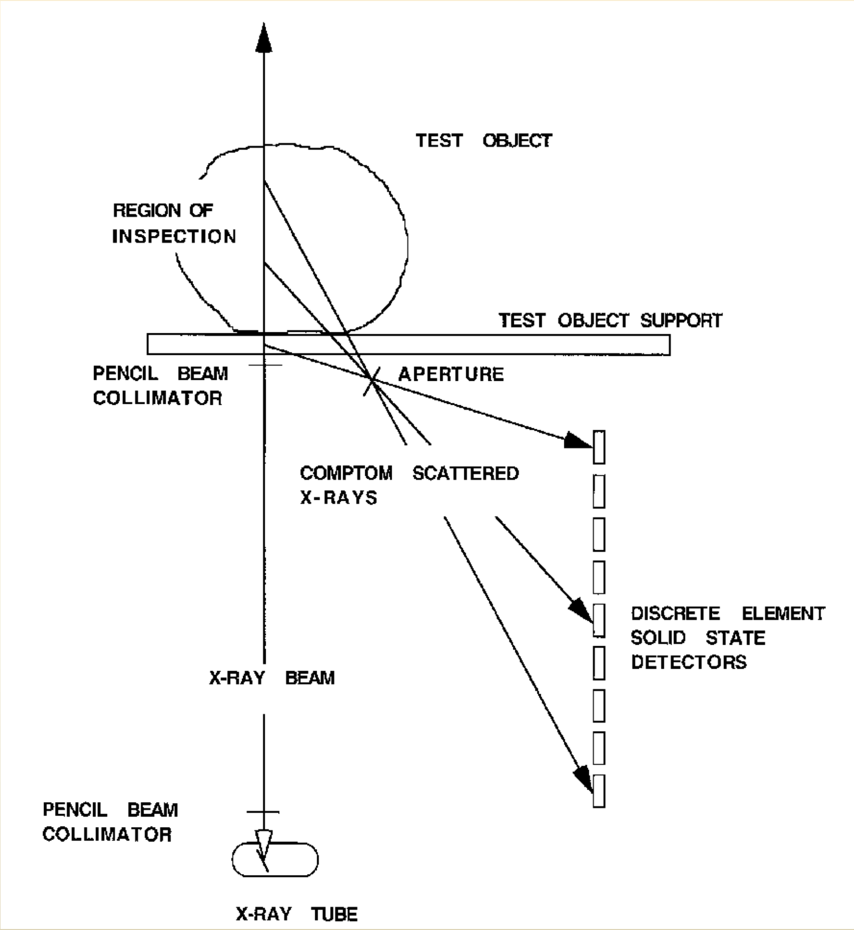
- Single-sided operation, suitable for large objects
- High contrast, for low-Z and high-Z materials
- Potentially high sensitivity and resolution
- No need for a large detector (although it helps)
- Easy-to-interpret signal (scattered intensity is roughly proportional to material density)

Traditional Compton Radiography



- Easy to implement
- Suffers from poor contrast due to surface glare
- Limited penetration capability
- Difficult to adapt for 3D data acquisition

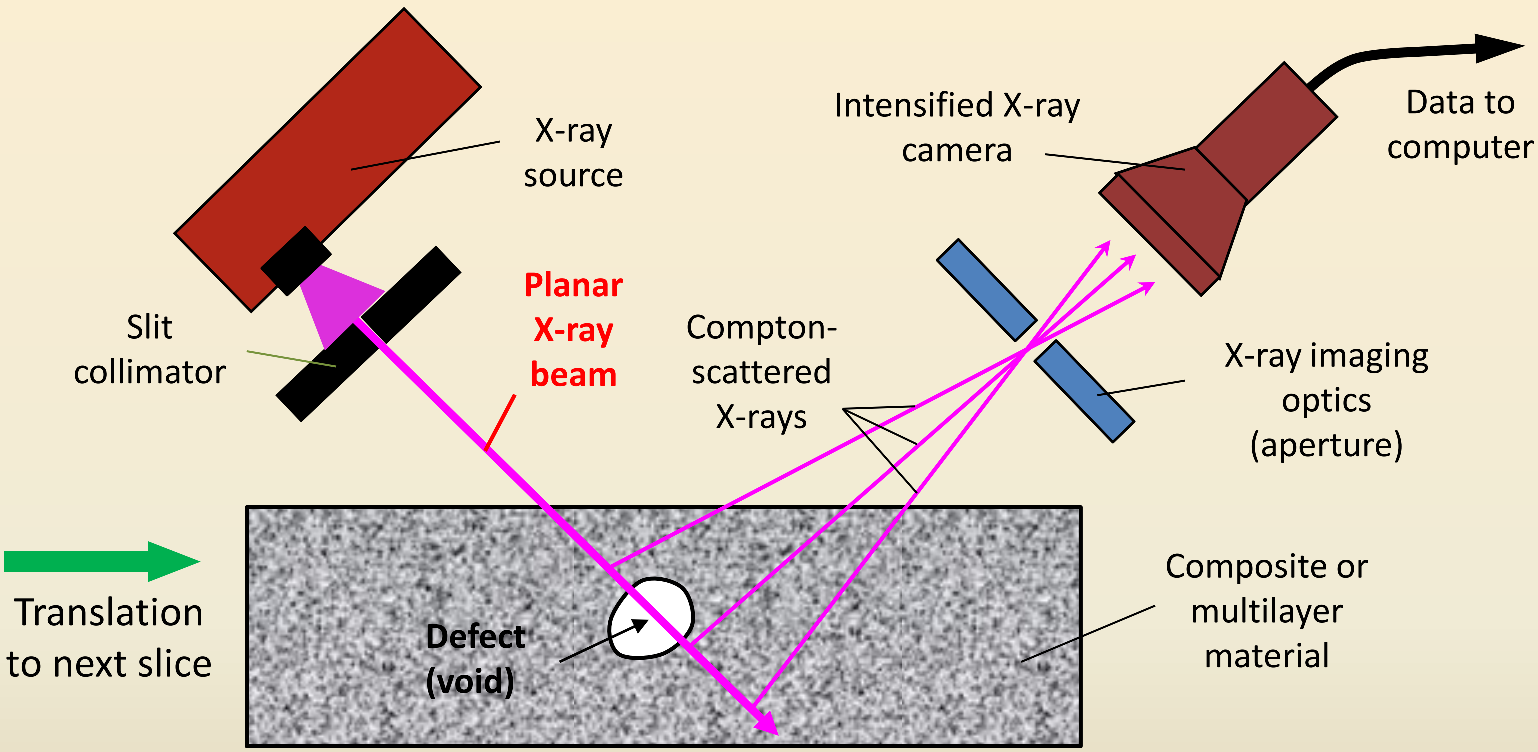
Pencil-Beam Compton Tomography



(from *ASTM Standard Guide for X-Ray Compton Tomography*)

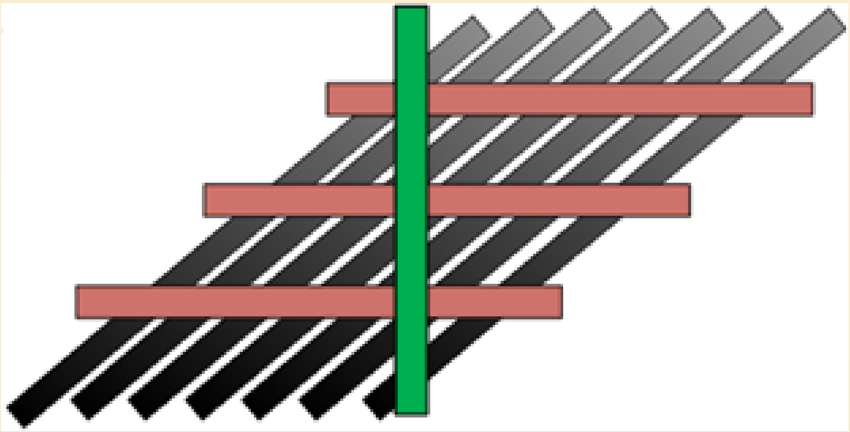
- Allows 3D data acquisition (*2D scanning with a 1D beam*)
- Slow scanning speed due to inefficient use of source
- Often requires bulky hardware (i.e., lead chopper)

Compton Imaging Tomography (CIT)

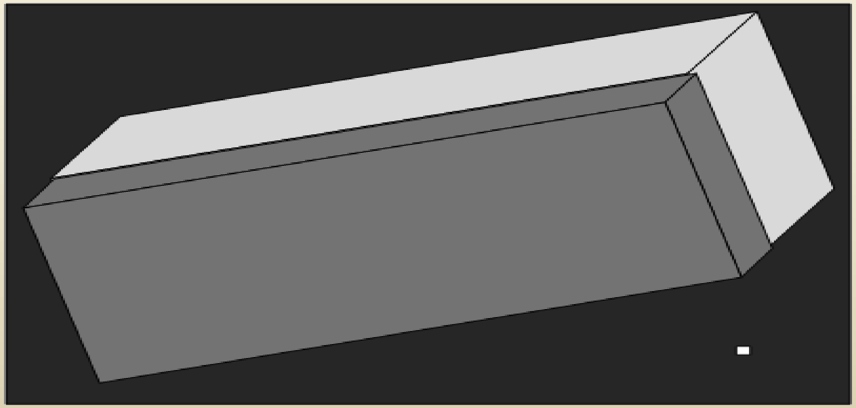


- Needs only **1D scanning** due to using a **2D beam** → Higher scanning speed!
- Uniform and high image quality (no surface glare), high contrast
- Transparent, slice-by-slice 3D data acquisition

Full 3D Structure Reconstruction from Tilted CIT Slice Images

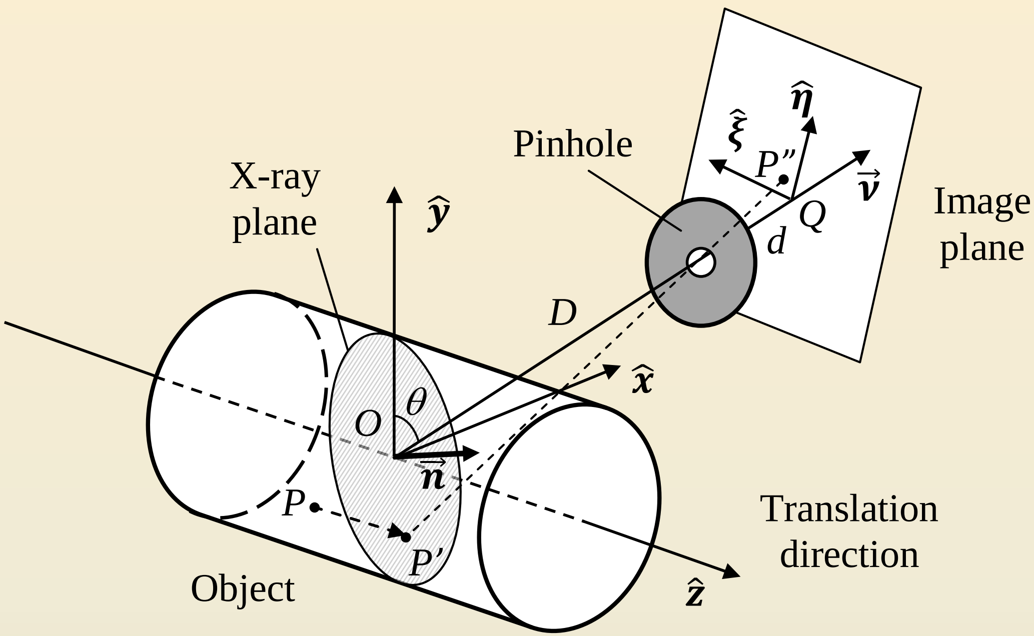


Any cross section can be reconstructed from a set of consecutive 2D Compton- scattered X-ray images.



Full 3D object structure is reconstructed from 2D Compton-scattered X-ray images.

CIT 3D Reconstruction Algorithm



For any point of the object ***P*(*x,y,z*)**:

1) Corresponding slice image number:

$$j = -\frac{1}{\Delta}\left(\frac{xn_x + yn_y}{n_z} + z\right)$$

2) Coordinates within slice *j*:

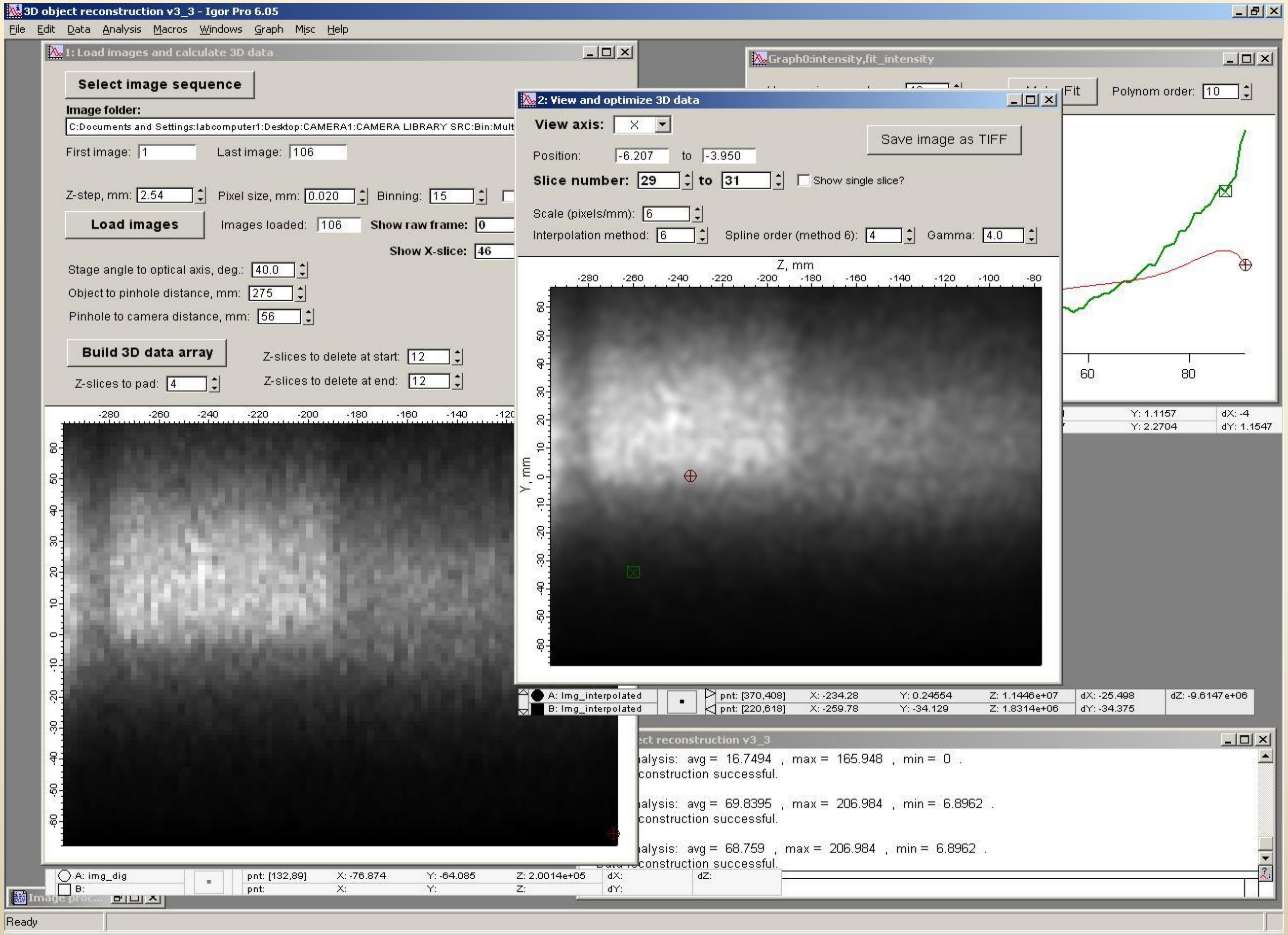
$$\xi = -d\,\frac{xv_z - z'v_x}{\left[D - \left(xv_x + yv_y + z'v_z\right)\right]\left|\sin\theta\right|}$$

$$\eta = -d\,\frac{y - \left(xv_x + yv_y + z'v_z\right)\cos\theta}{\left[D - \left(xv_x + yv_y + z'v_z\right)\right]\left|\sin\theta\right|}$$

Δ – slice-to-slice displacement

The 3D reconstruction algorithm is relatively easy to implement (in comparison to Radon transform used in CT). Computations do not introduce artifacts.

CIT Software for Data Reconstruction, Image Processing, Display, and Analysis



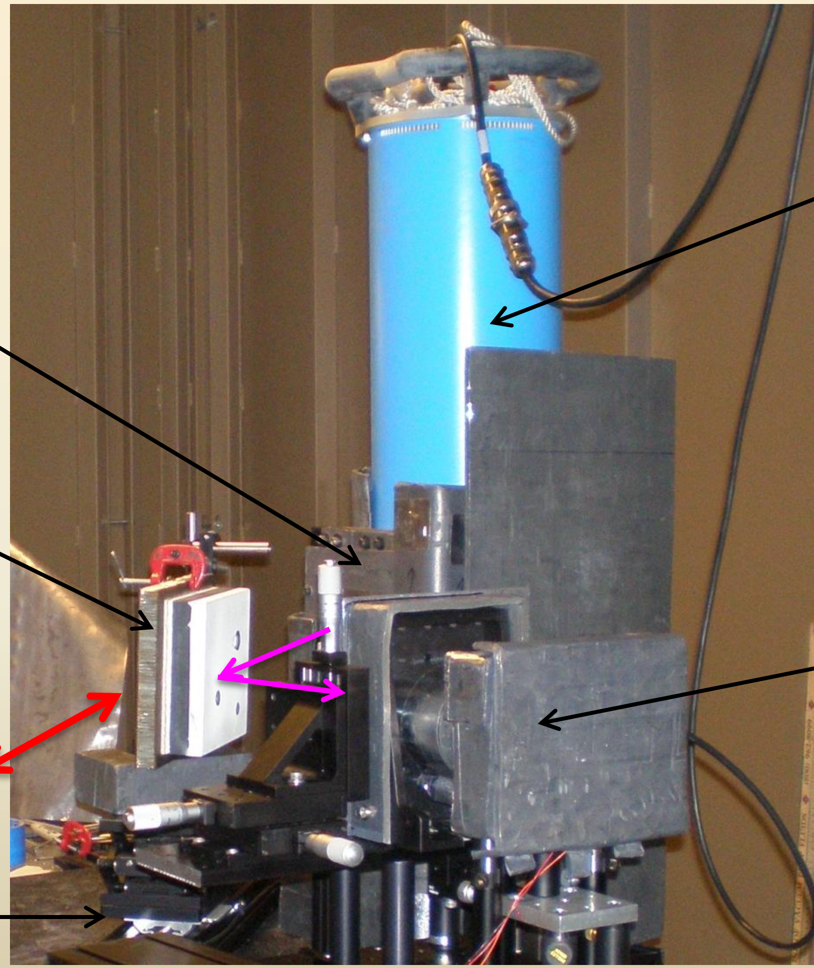
Current CIT Prototype Based on a 225-kV X-ray Source

Vertical 2-mm lead slit

Mounted test object

Translation at 10 - 20 s per 1-mm slice

Translation stage



X-ray source

X-ray camera

Typical CIT Penetration Depth with a 200 – 250 kV Source

Material	Chemical Composition	Density, g/cm^3	X-ray Att. Coef. @100 keV, cm^2/g	Penetration Depth, cm
Aluminum	100% Al	2.7	0.17	4.2
Avcoat	~50% SiO_2, 50% C	0.5	0.16	24
C/C composite	100% C	1	0.15	14
Silica ceramics	100% SiO_2	1.5	0.17	8
Titanium	100% Ti	4.5	0.272	1.6
SS304 stainless steel	70% Fe, 20% Cr, 9% Ni, 1% Si	8.06	0.365	0.7

Experimental penetration depth estimate:

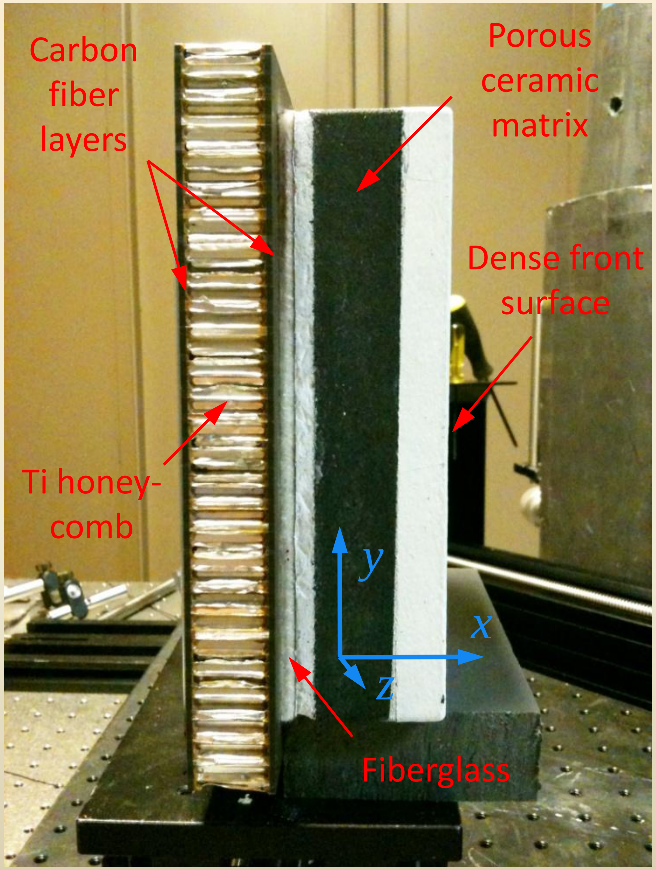
$$L_{CIT}(E) \sim 2L_{att}(E) = \frac{2}{\sigma(E)\rho}$$

$\sigma(E)$ – scattering cross section for photon energy E~80-100 keV
ρ – material density

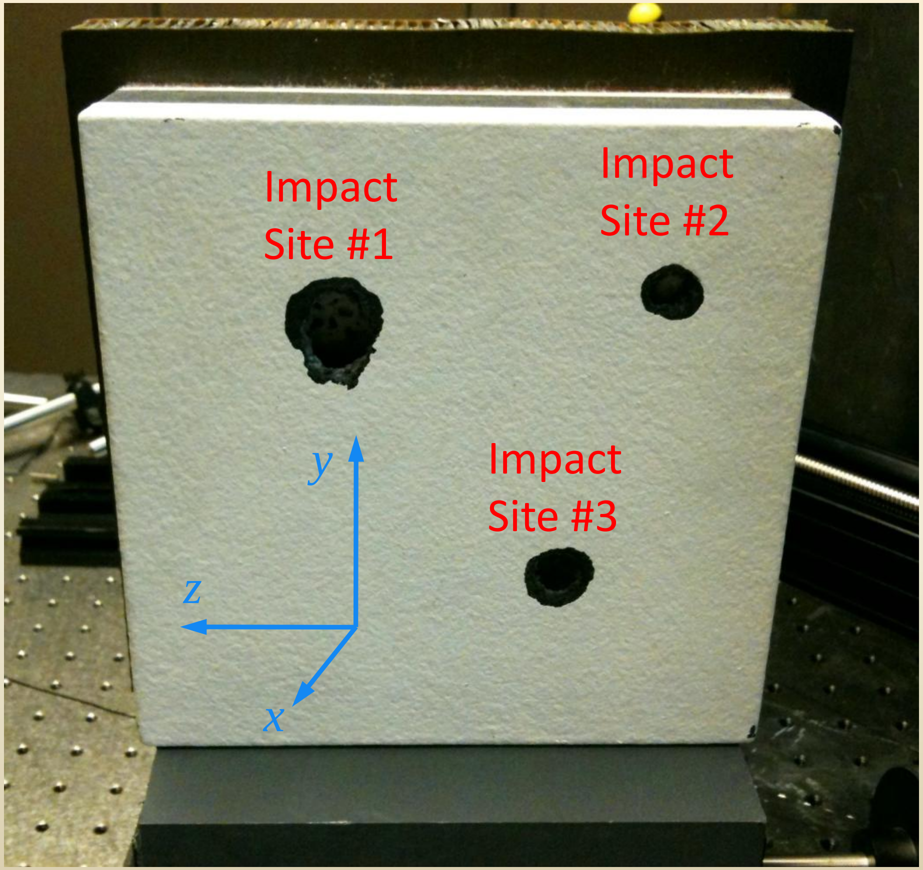
Examples of CIT Applications

NASA Thermal Insulation Tile with Simulated Micrometeoroid Impacts

Side View



Front View



Selected coordinate system is shown in blue

Impact Site #1

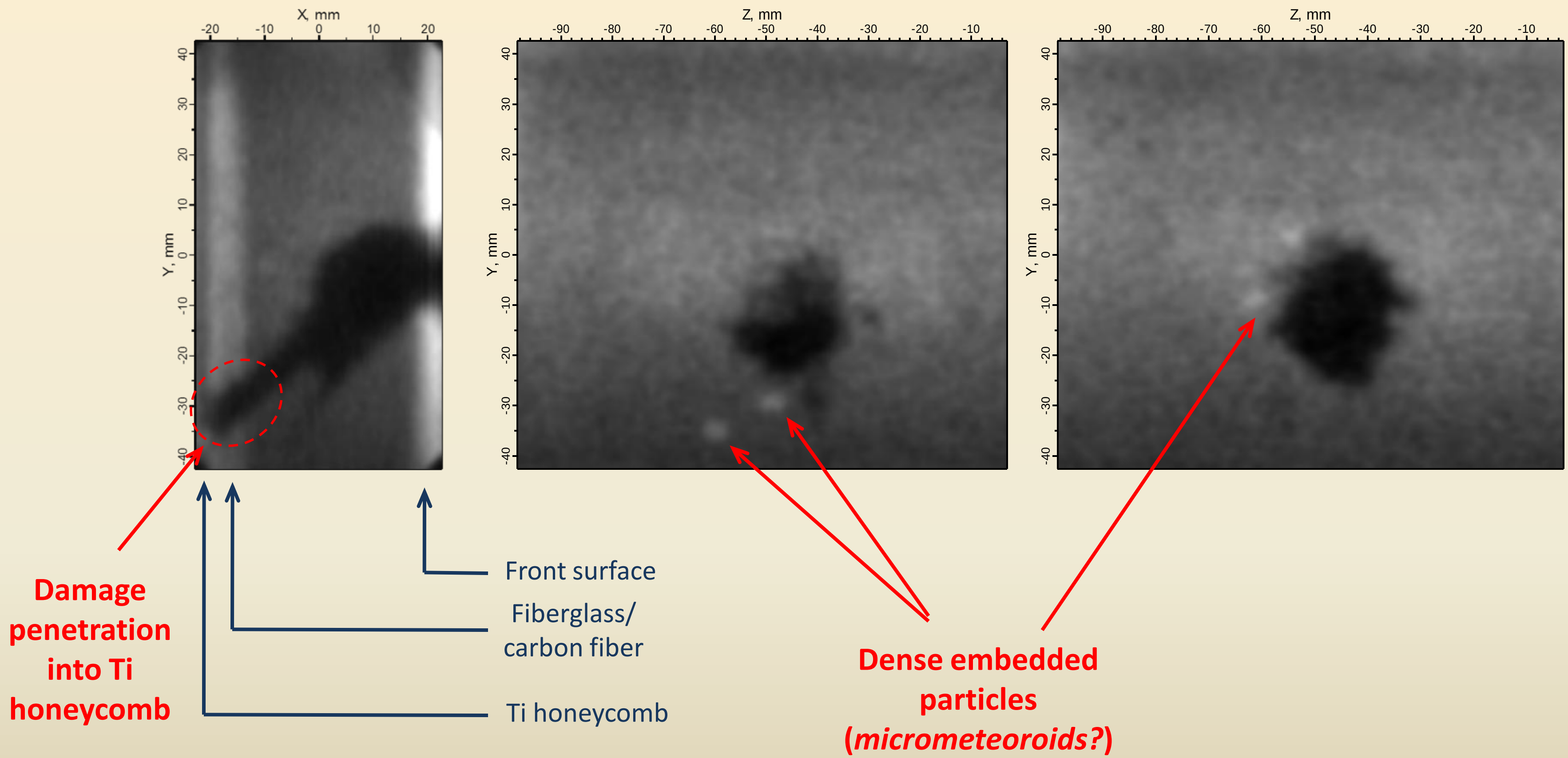
View parallel to tile surface

Views perpendicular to tile surface

z = -42.4 mm

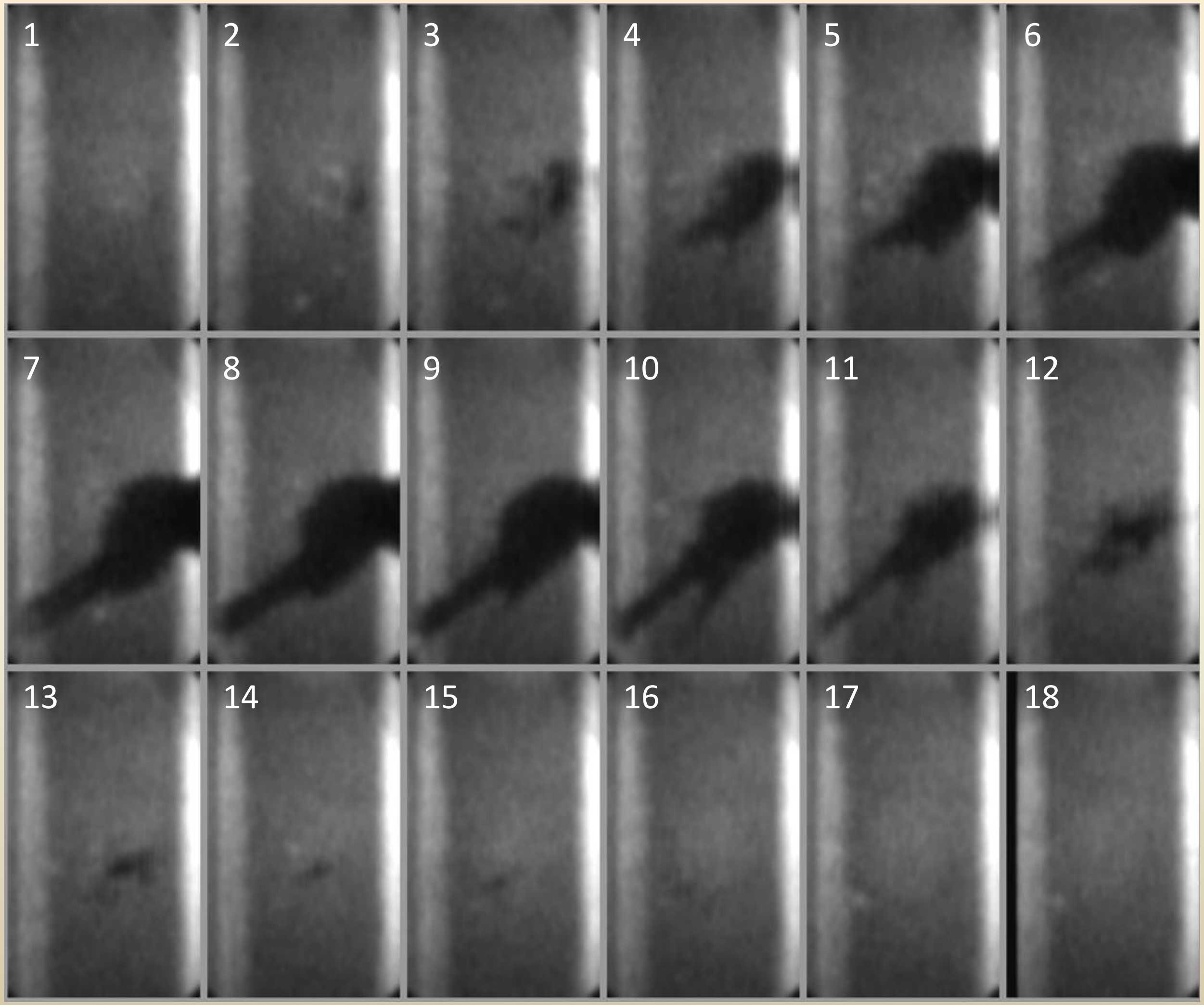
x = +3.1 mm

x = -0.3 mm

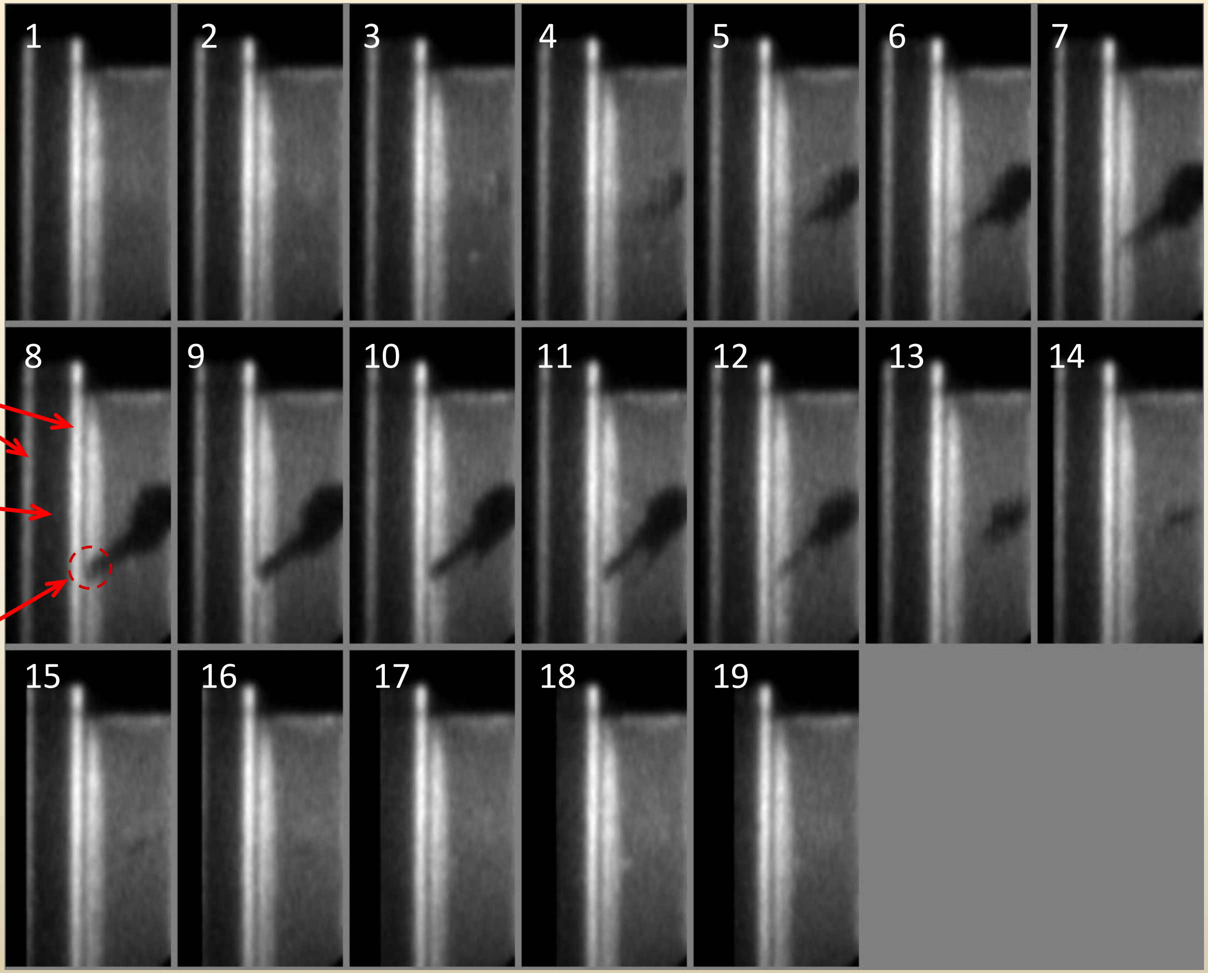


CIT detected **deep damage penetration** (likely all the way to the Ti honeycomb) at Impact Site #1, with **multiple dense fragments** scattered around the hole.

Impact Site #1: Consecutive Slices in Z-Direction (Side View of the Hole)



Impact Site #1: Consecutive Slices in Z-Direction With Expanded Field of View

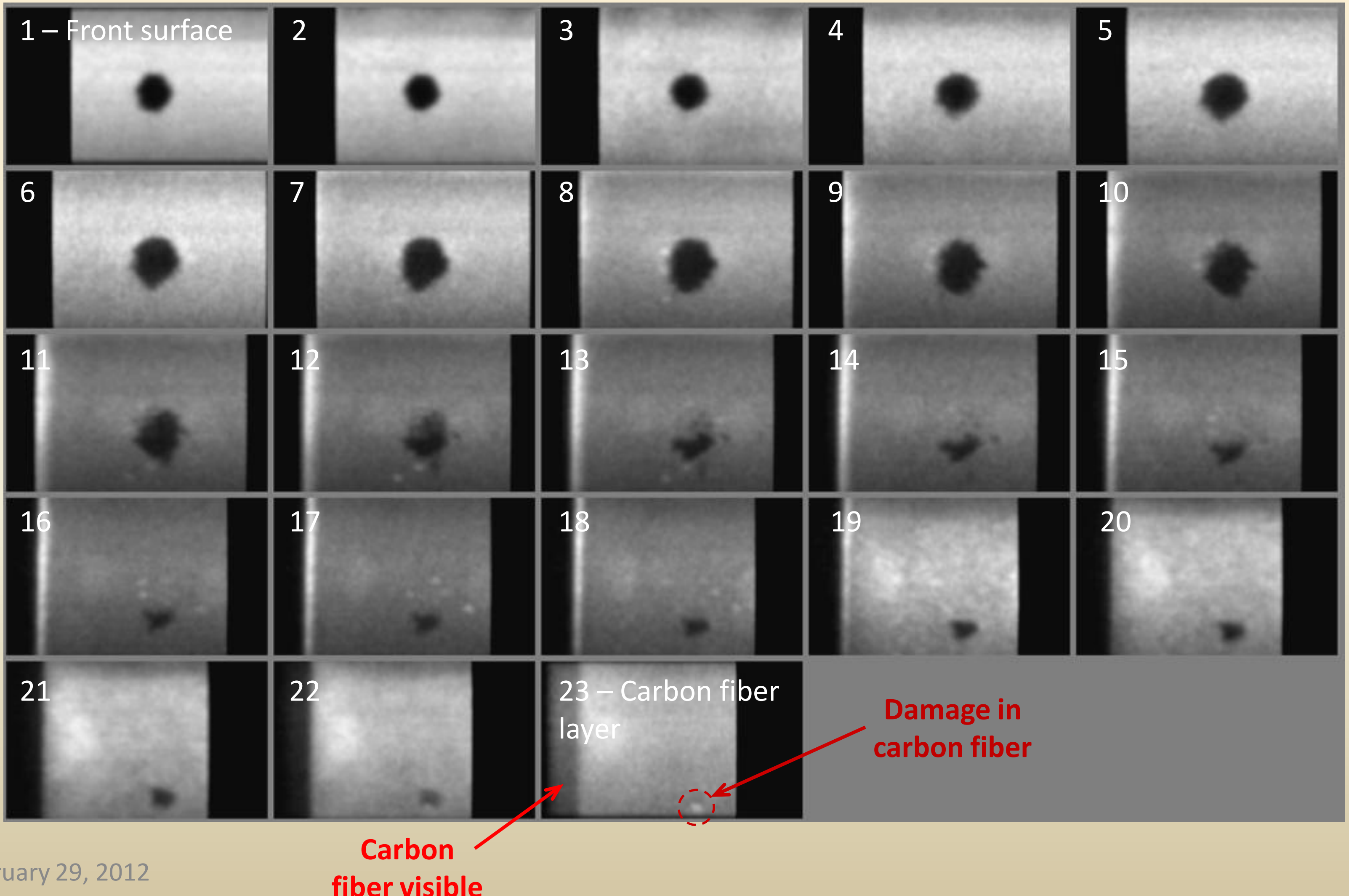


Carbon fiber layers

Ti honeycomb

Damage stops before the first carbon fiber layer

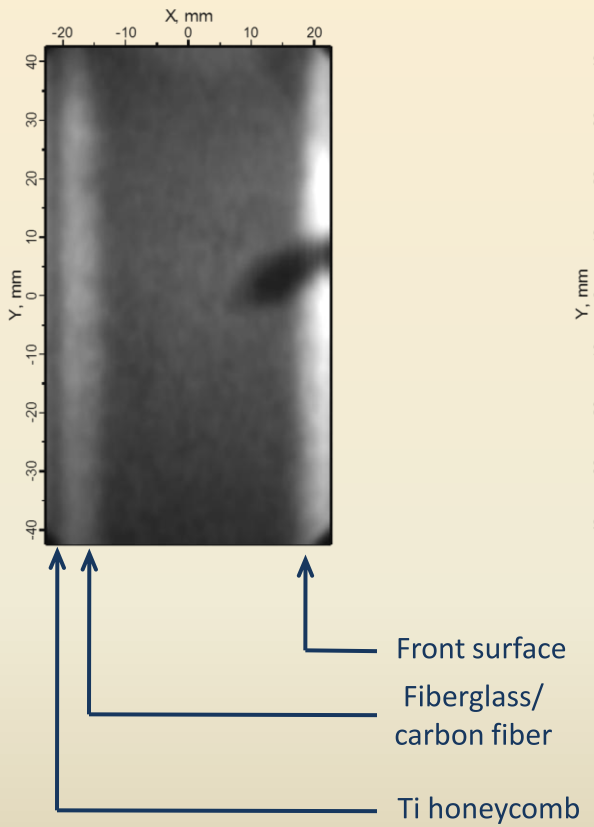
Impact Site #1: Consecutive Slices in X-Direction (Front View of the Hole)



Impact Site #2

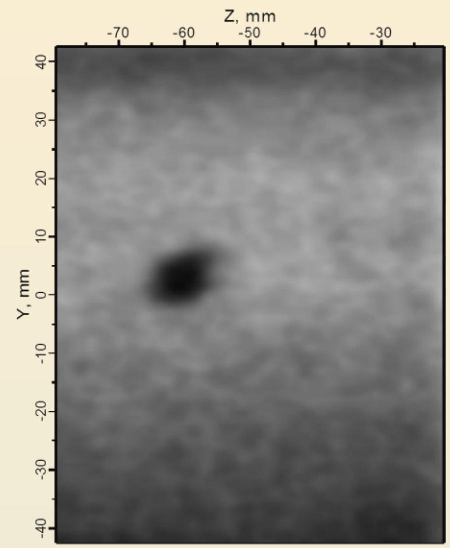
View parallel to tile surface

z = -60 mm



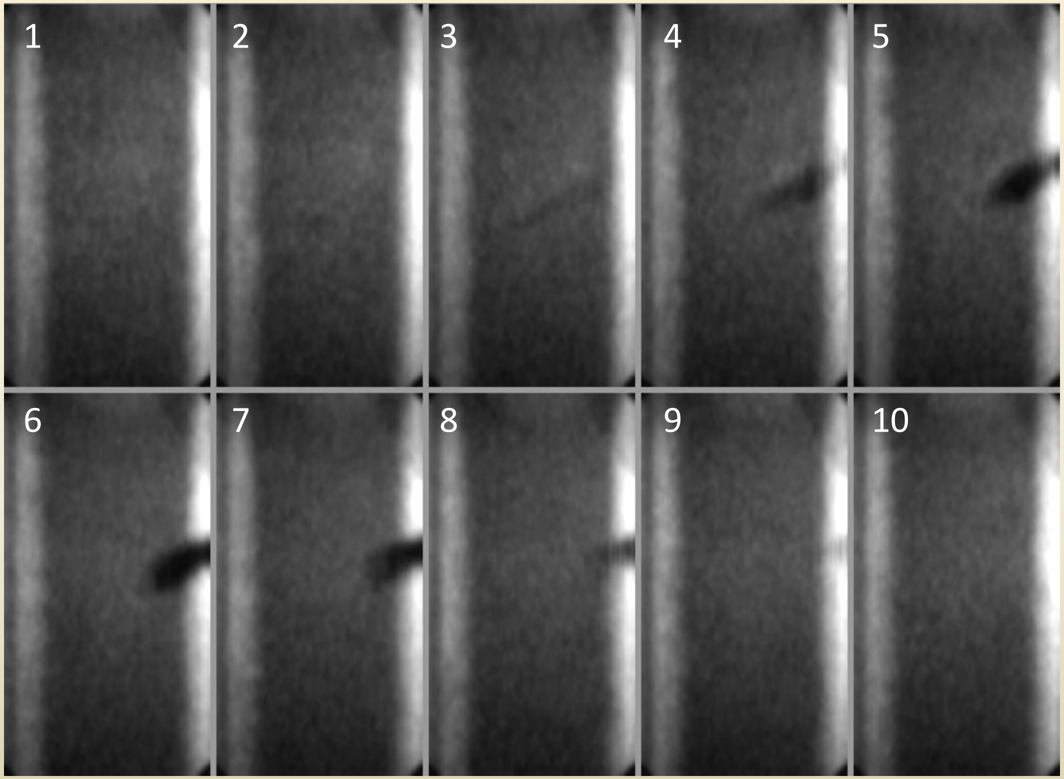
View perpendicular to tile surface

x = +14.5 mm

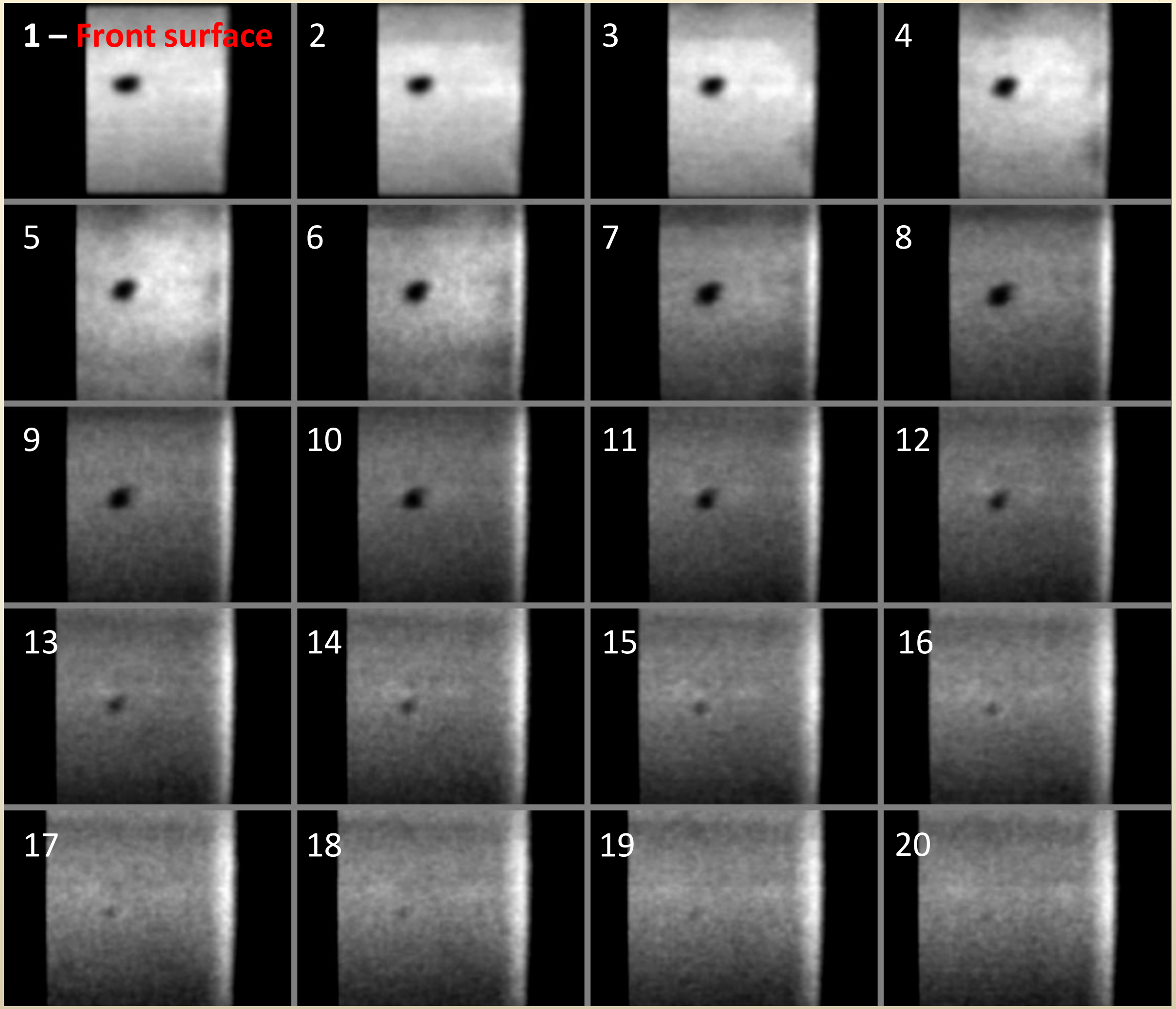


CIT detected **shallow damage penetration** at Impact Site #2, with the largest hole diameter ~7 mm at a depth of 9 mm.

Impact Site #2: Consecutive Slices in Z-Direction (Side View of the Hole)



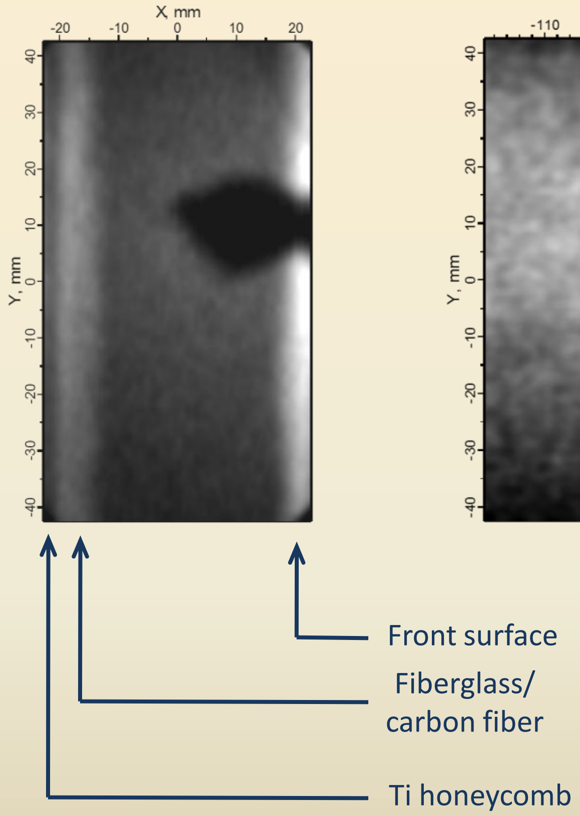
Impact Site #2: Consecutive Slices in X-Direction (Front View of the Hole)



Impact Site #3

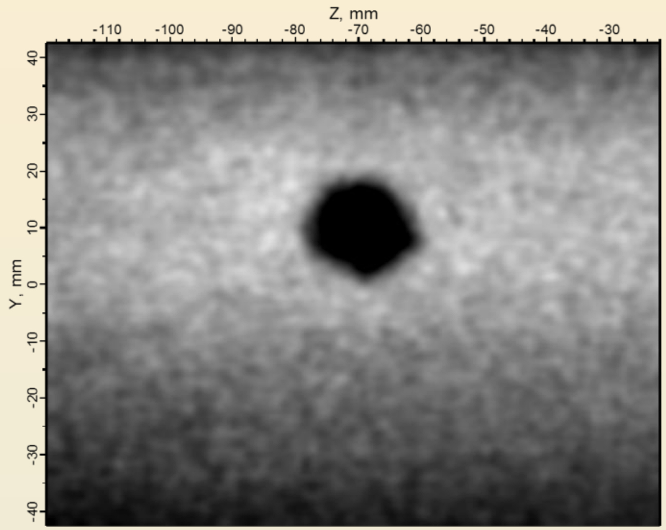
View parallel to tile surface

z = -69.2 mm



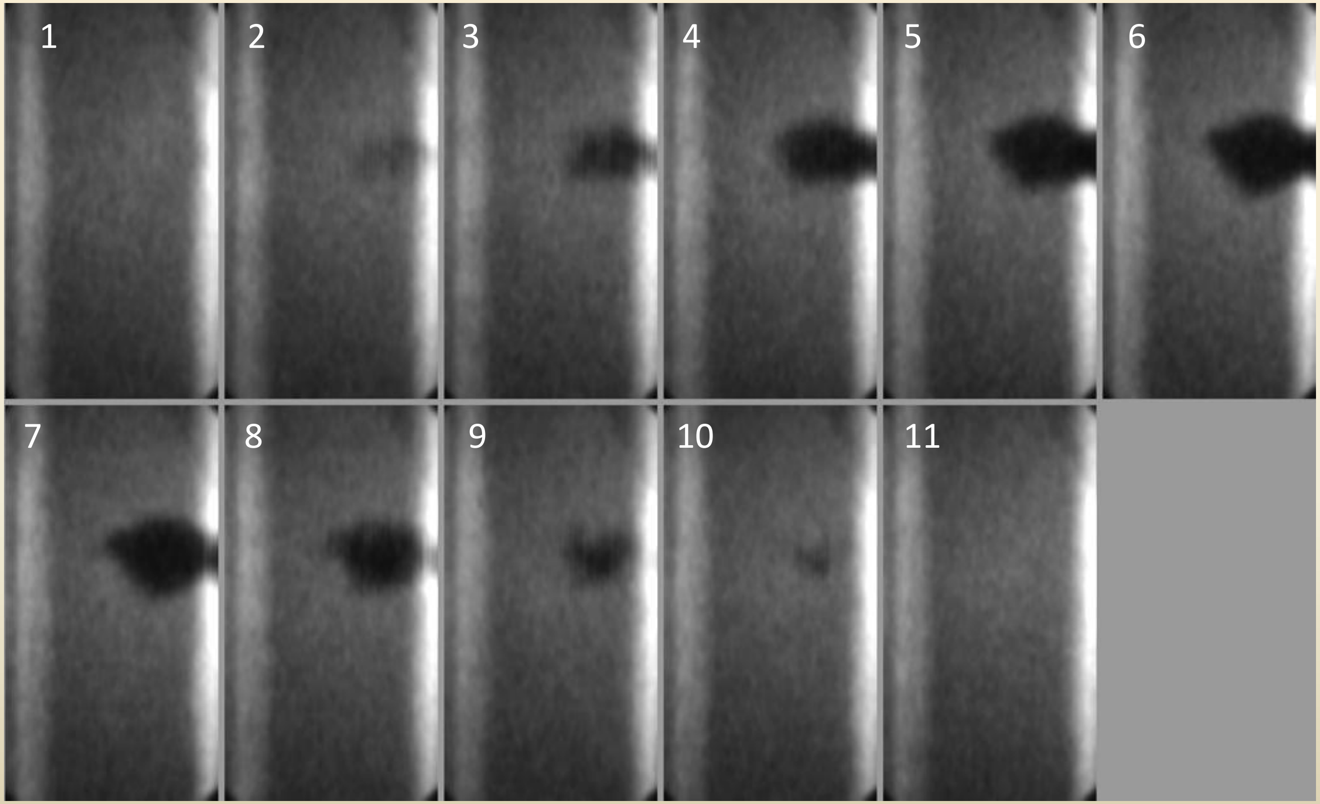
View perpendicular to tile surface

x = +11.1 mm

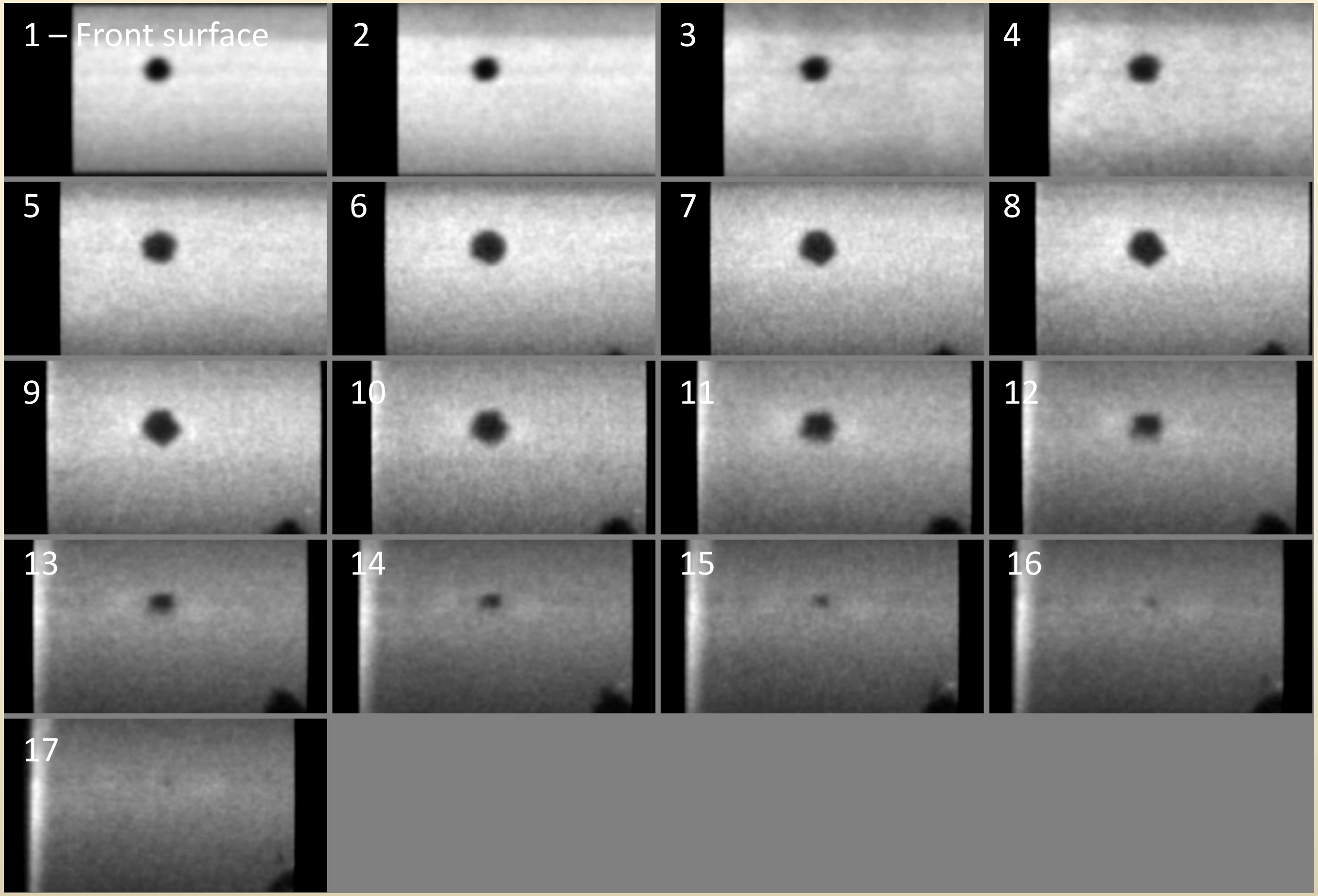


CIT detected **medium damage penetration** (halfway through the porous ceramic layer) at Impact Site #3, with the largest hole diameter ~12 mm at a depth of 12 mm.

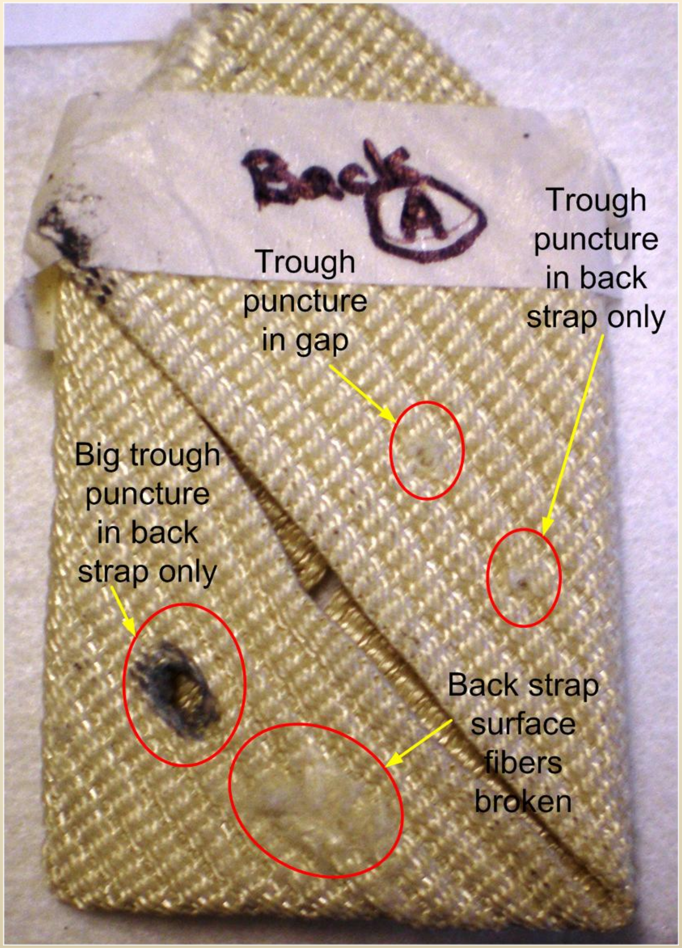
Impact Site #3: Consecutive Slices in Z-Direction (Side View of the Hole)



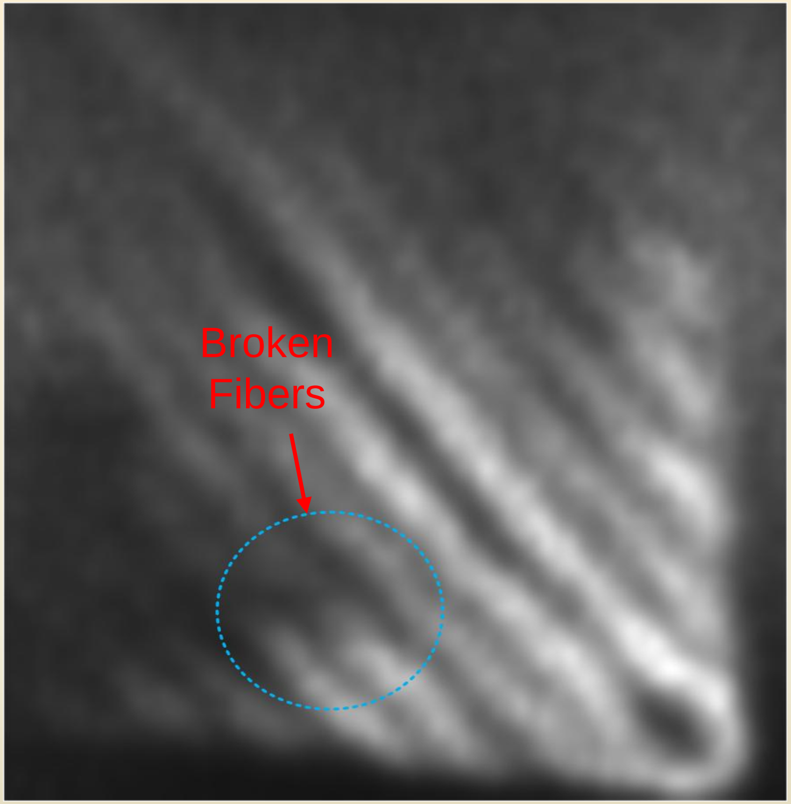
Impact Site #3: Consecutive Slices in X-Direction (Front View of the Hole)

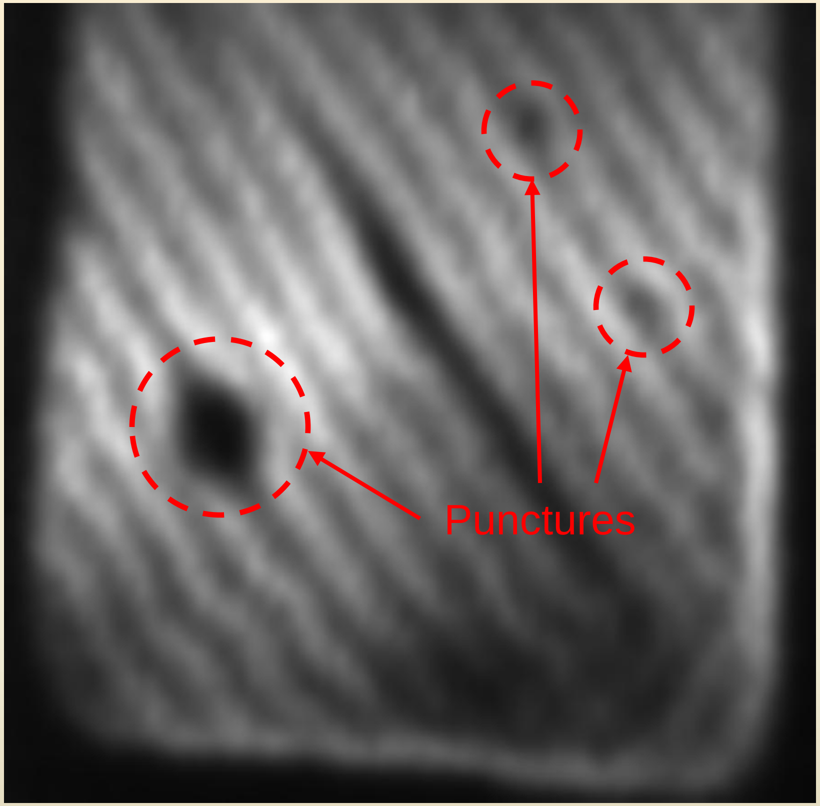


NASA Habitable Enclosure: Aramid Reinforcement Belt with Simulated Defects



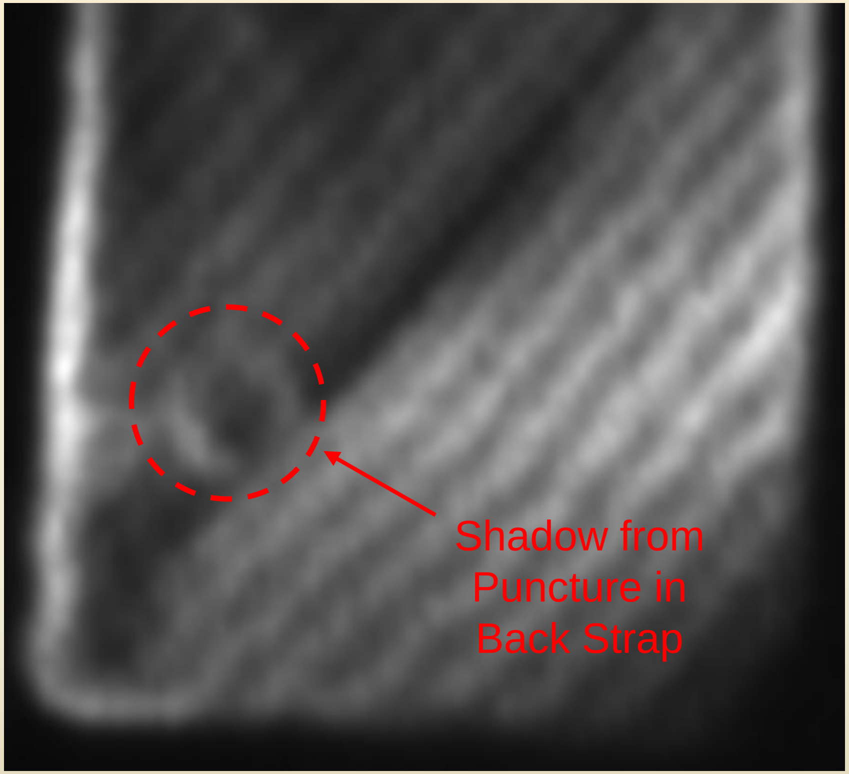
CIT Images of the Back Strap

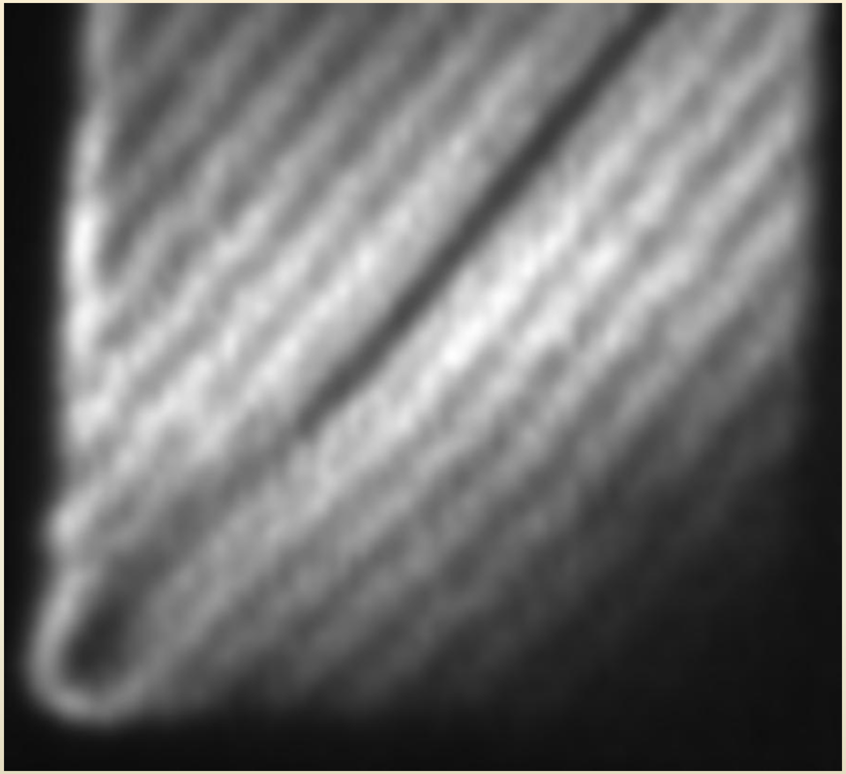




- All defects (including damaged fibers) are easily visible.
- Each strap can be resolved separately.

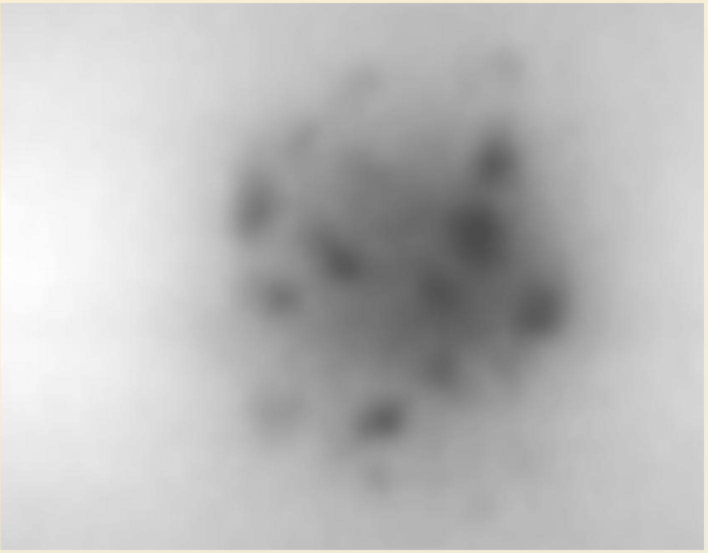
CIT Images of the Front Strap





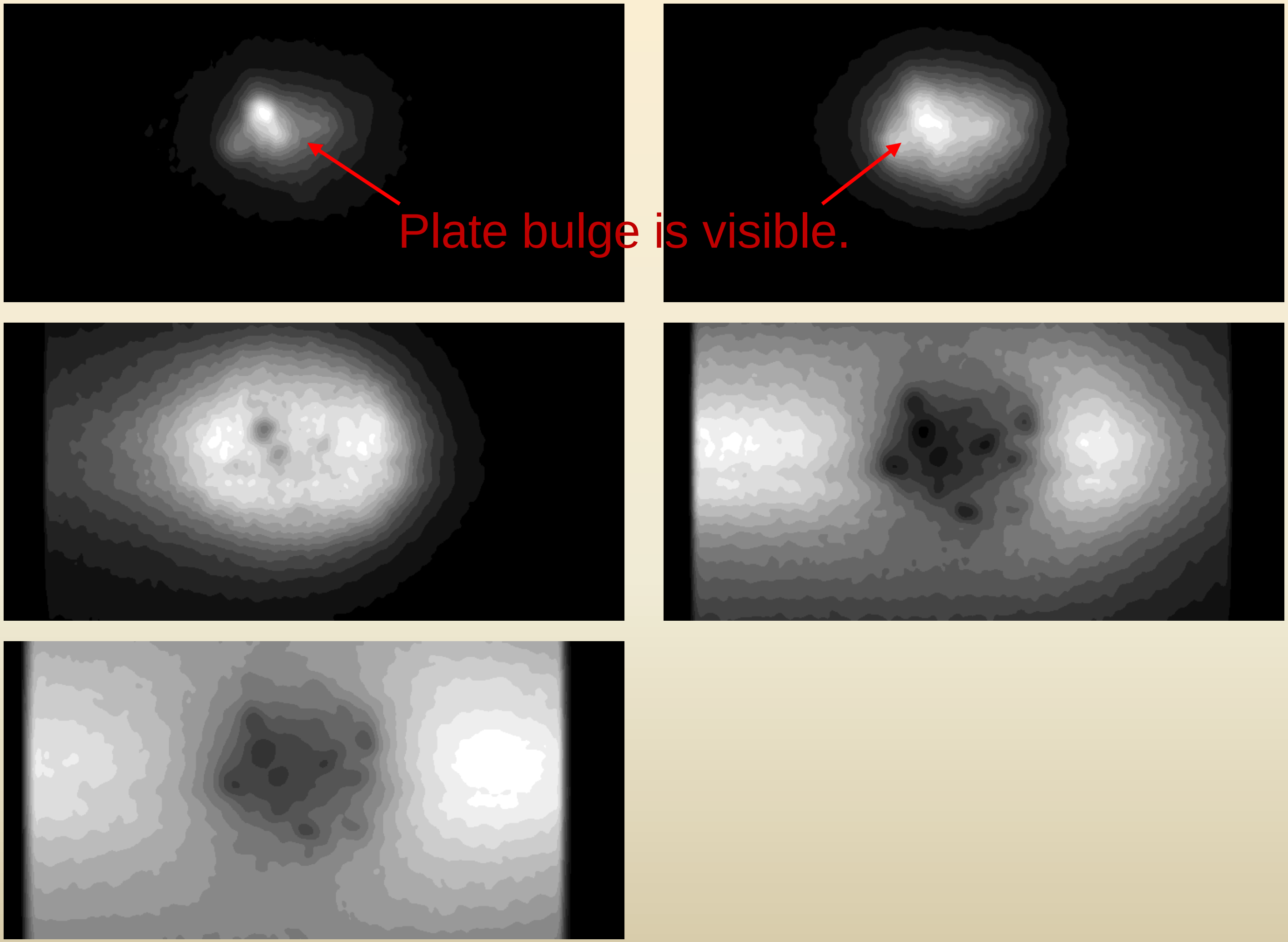
Sample of ISS Pressure Wall Impact

Sample photo

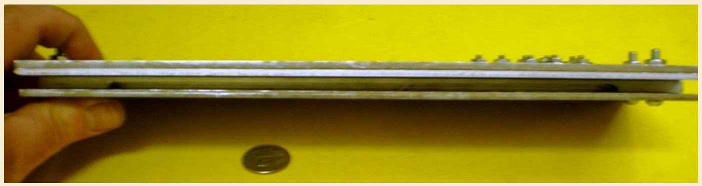
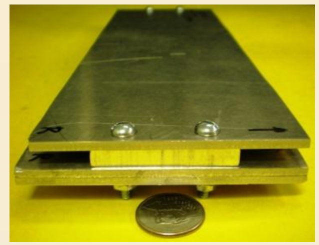


Corresponding backscatter X-ray image

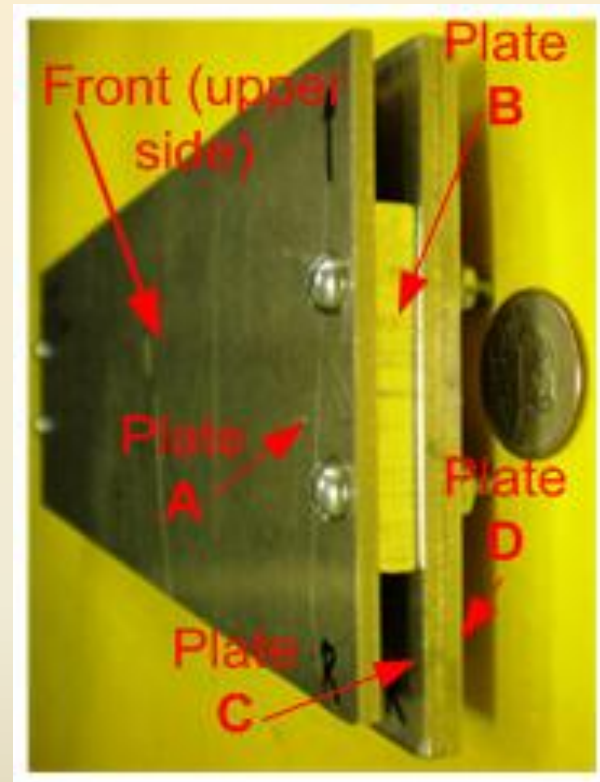
CIT Images of ISS Pressure Wall Sample: Much Higher Contrast!



CIT Experimental Results: Simulated Al Multilayer Aerospace Component with Corrosion

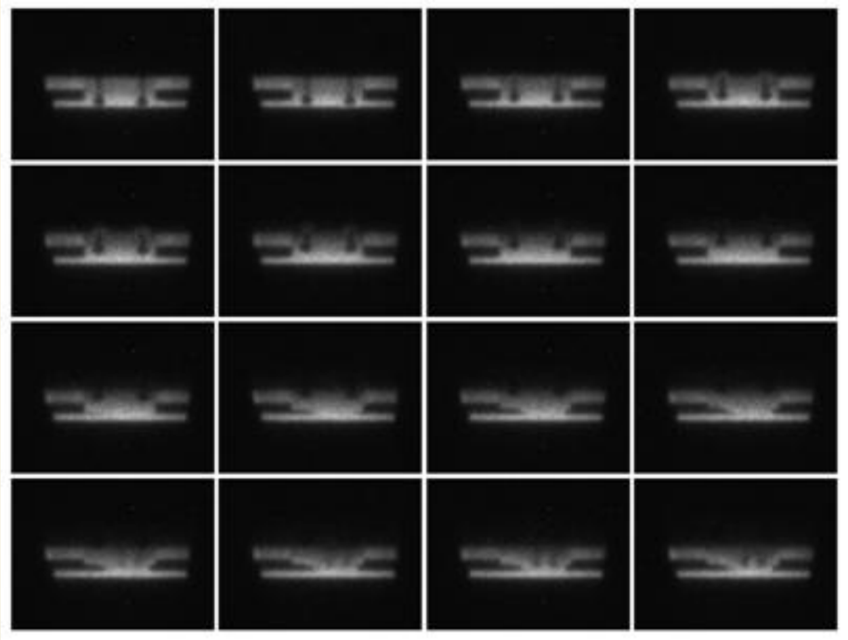



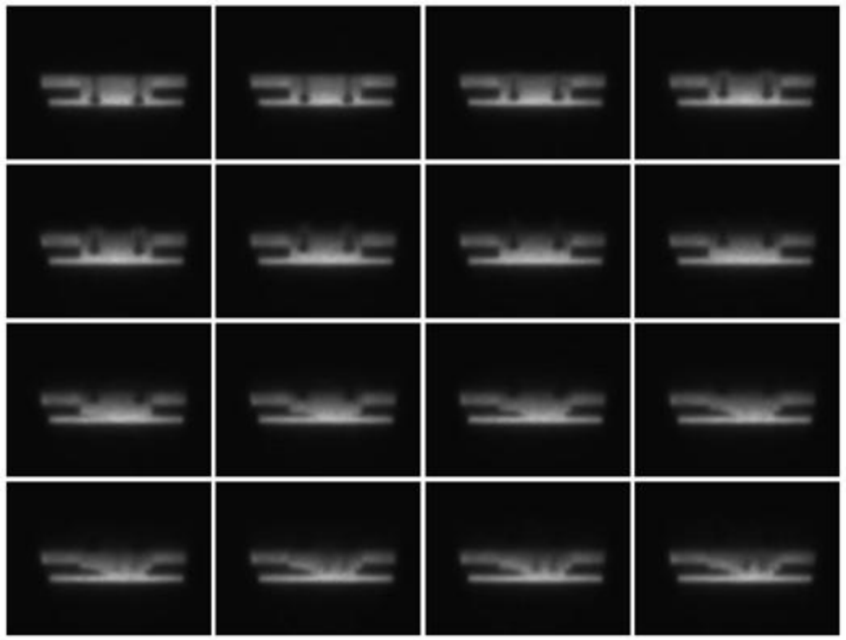




CIT multilayer aluminum alloy sample with simulated interlayer corrosion

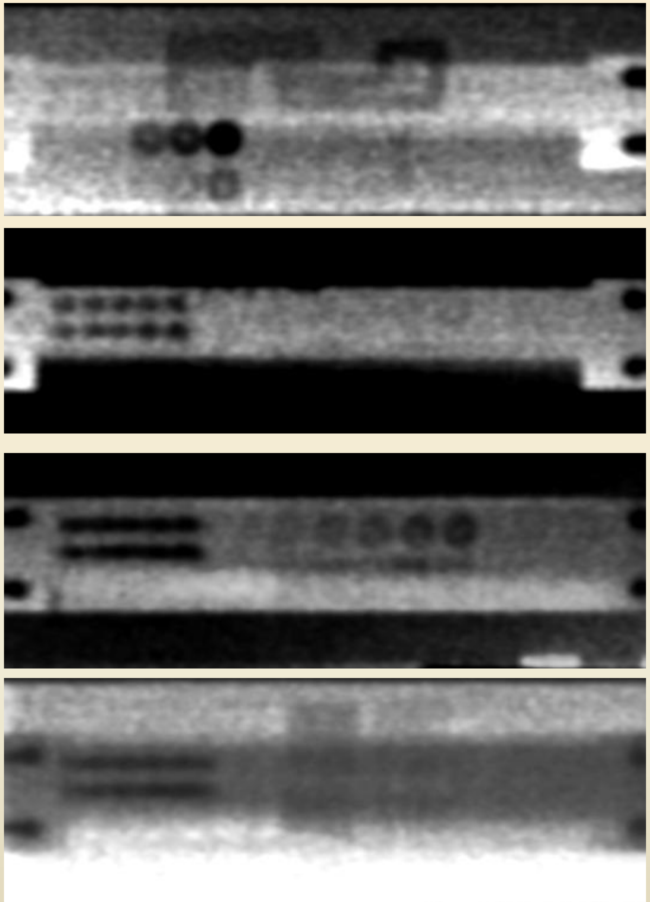
Cross Sections of Individual Images of the Sample



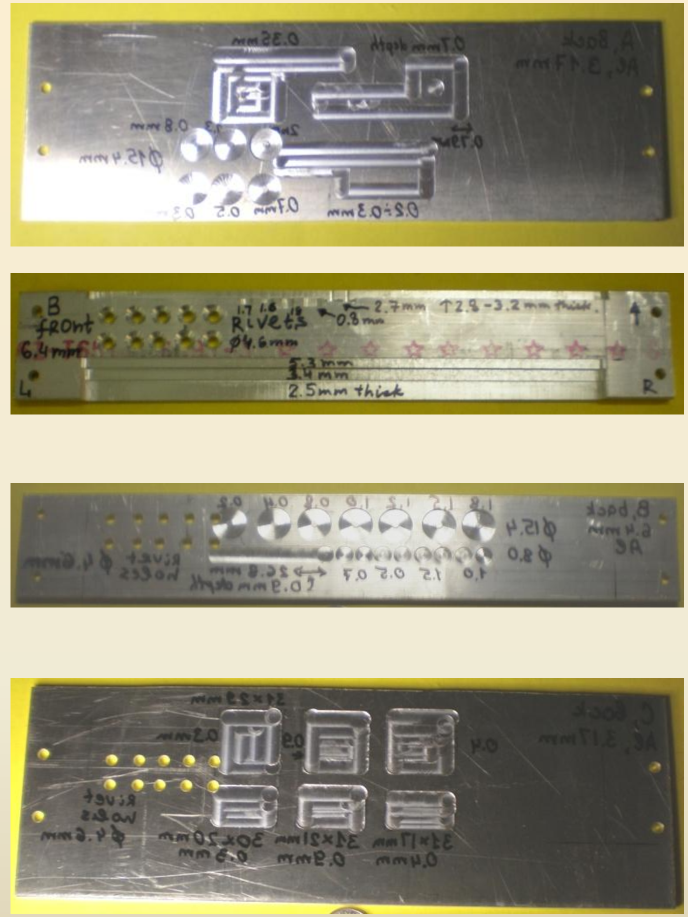


Examples of raw 2D Compton-scattered X-ray images (left) and denoised images (right) of slices of the multilayer aluminum alloy part. Only 16 images of ~100 taken are shown.

Reconstructed Cross Sections of Individual Plates



2D x-sections of the coupon obtained from its CIT-produced 3D structure

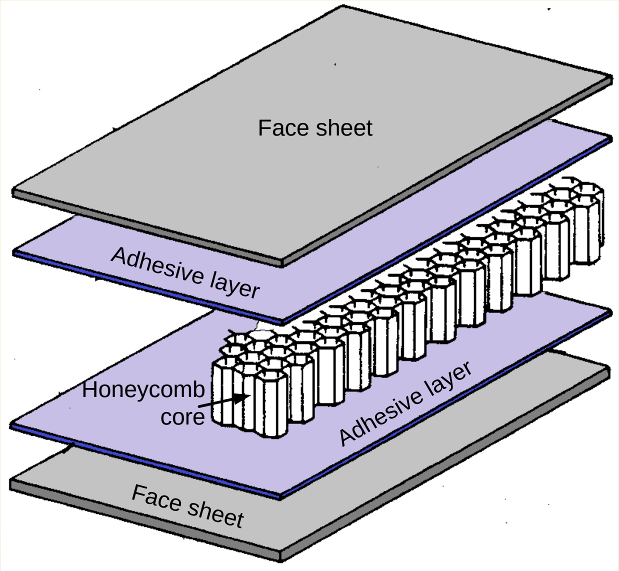


Photos of the actual coupon layers

Spatial resolution ~1.5 – 2 mm

Depth resolution ~0.2 – 0.3 mm (~2% density difference)

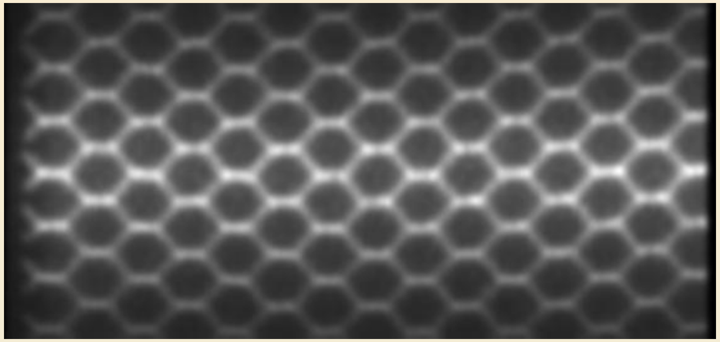
NDI of Honeycomb Structures



COTS aluminum honeycomb composite panel (1/2-in. thick)

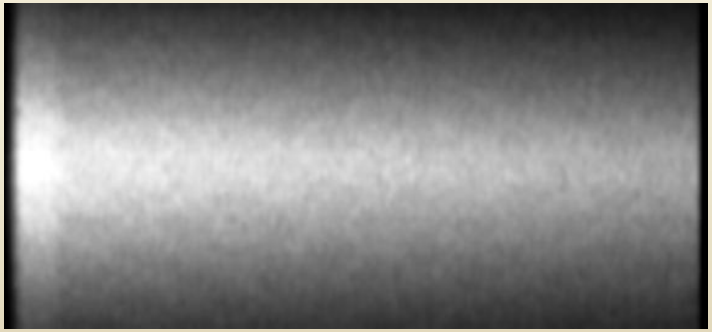
CIT Views of Honeycomb Structure Cross Sections

Front face



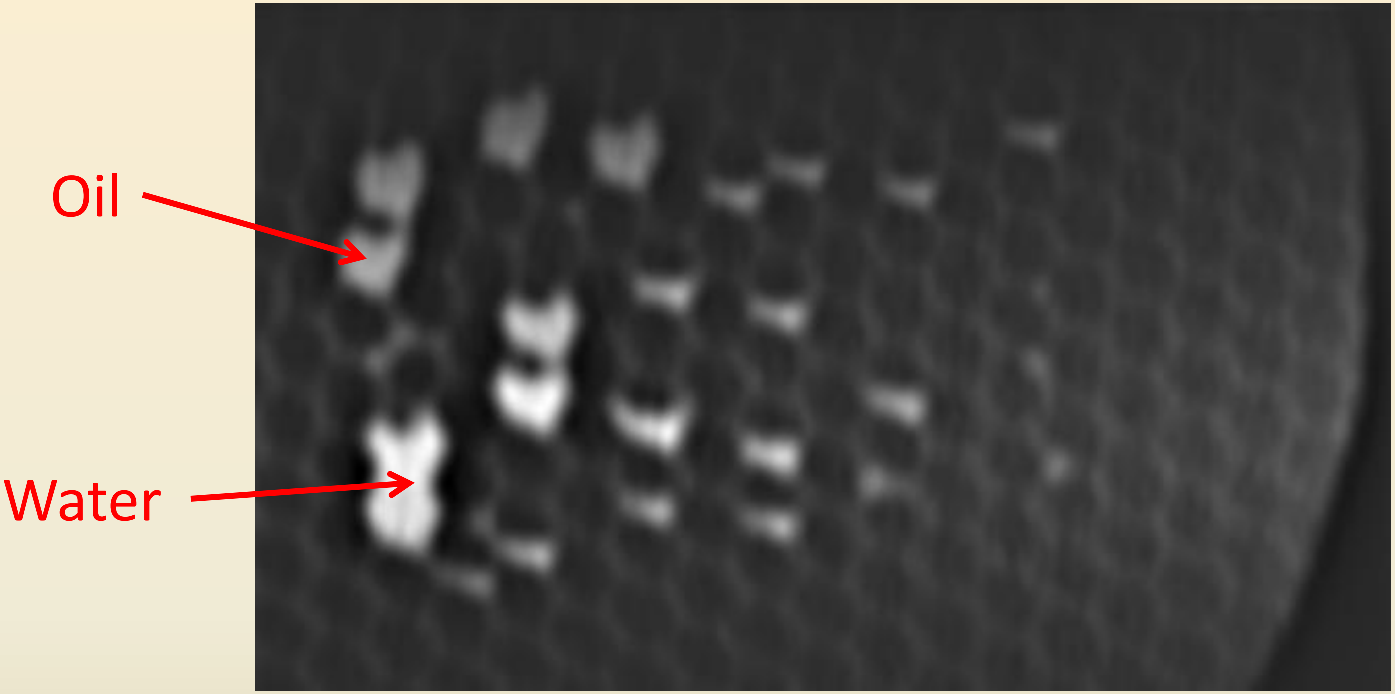
Core

Rear adhesive layer



Rear face

Liquid Penetration of Honeycomb Structure

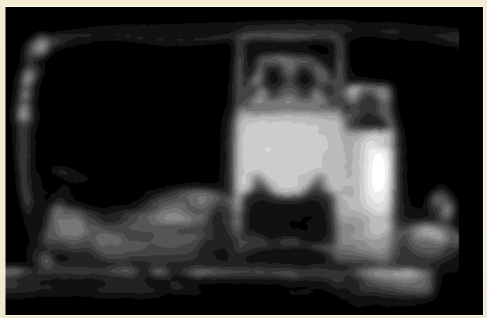


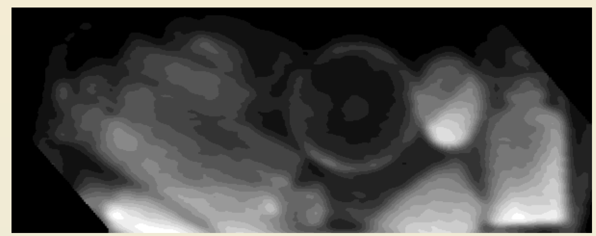
Water and oil can be differentiated because of their different densities

Application of CIT to Security Inspection and Contraband Detection

Travel bag with accessories (closed for the experiment)

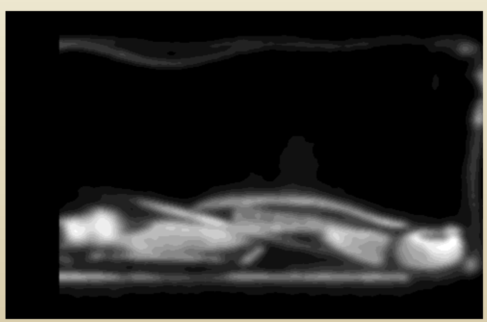
Vertical cut through the middle part (~1.5 cm thick)

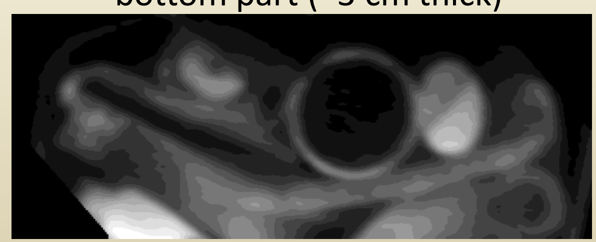




Horizontal cut through the bottom part (~3 cm thick)

Vertical cut through the front part (~2 cm thick)





Horizontal cut ~3 cm from the bottom (~2.5 cm thick)

Wish List for Most Applications:

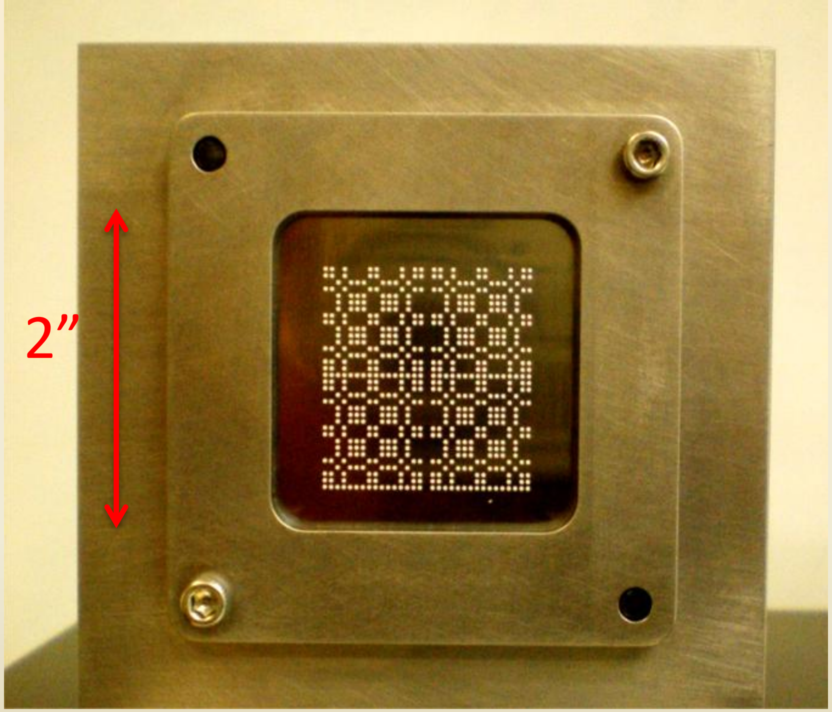
- Smaller size, weight, and power (SWaP) consumption
- Higher resolution
- Wider field of view
- Faster operation

Although most of these parameters are interrelated, system configuration is a tradeoff that favors the most critical parameters.

General Prescriptions for Improving System Performance

- **Reduce kV source whenever possible** (lower weight due to smaller shielding; lower power consumption)
- **Radioisotope source vs. X-ray tube** (small weight, no power needed; but safety issues)
- **Improve photon collection efficiency**
- **Improve image processing**

Current Work: Development of Coded-Aperture Optics for Faster Image Acquisition



Larger open area fraction → Potential speed improvement by **>10X**

Thank you for your attention!

Questions?